NORMALLY-CLOSED, LEAK-TIGHT PIEZOELECTRIC MICROVALVE UNDER ULTRA-HIGH UPSTREAM PRESSURE FOR INTEGRATED MICROPROPULSION

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ABSTRACT

This paper presents a leak-tight piezoelectric microvalve, operating at extremely high upstream pressures for microspacecraft applications. The device is a normally-closed microvalve fabricated mostly by the micromachining of silicon wafers. The microvalve consists of a custom-designed piezoelectric stack actuator bonded onto silicon valve components, such as the seat, boss and tether, in a stainless steel housing. Major seating configurations include narrow edge seating rings and tensile-stressed silicon tethers that contribute to the desired normally-closed leak-tight operation. The microvalve operations have been demonstrated with a 'helium leak detector scale' leak rate of 10^{-4} sccm at 800 psi. Dynamic microvalve operations of up to 1 kHz have been successfully demonstrated at the pressures in the range of 0~1000 psi. The measured static flow rate of a microvalve with an applied potential of 10 V is 52 sccm at an inlet pressure of 300psi. The measured power consumption, to hold the microvalve seat fully open, is 3 mW with the applied potential of 30 V. The measured dynamic power consumption is 180 mW for 100 Hz continuous operation at 100 psi.

INTRODUCTION

Constellations of microspacecrafts (10 kg total mass) are being envisioned to study magnetic fields or radiation belts around the Earth [1]. Mission studies involving such spacecraft configurations are mainly under NASA's Space Science Sun-Earth-Connection. By using large constellations, tensor mapping of fields and particles may be conducted. The Magnetic Constellation mission, which has recently been approved by NASA, seeks to map Earth's magnetic field with 50 – 100 spacecrafts, each equipped with its own magnetometer. Such large constellations of spacecraft are only feasible if very small spacecraft are used in order to keep the total launch mass reasonable and the launch cost affordable.

Constellation spacecraft may have propulsive requirements, either to maintain a formation, or to turn (slew) the spacecraft to point an antenna to Earth for data transmission, or to aim a camera for observation. In case of such small spacecraft, significant propulsion system size and mass reduction over current state-of-the-art is required for these subsystems to fit within the greatly reduced mass and size envelope. Thrust and impulse bit capabilities may also be required to be very small depending on spacecraft mass and required pointing accuracy. Required impulse bits may range from the mNs-range for larger craft having relatively coarse attitude requirements, into the μNs-range and possible even nNs-range for very tight pointing requirements and very small spacecraft. Thus, there exists a need for very low impulse bit, micro-Newton thrust level propulsion systems in order to provide the required pointing accuracies for the attitude control of the microspacecraft [2]. Such micropropulsion systems require precisely controlled, extremely small propellant flow from a pressurized propellant tank. A fast actuation, leak-tight microvalve at high propellant pressures is required for micropropulsion applications as described in Table 1. Ideally, this valve will be tightly integrated with thruster components to allow for a compact and lightweight overall thruster module design.

Table 1. Microvalve requirements for NASA's miniature spacecraft propulsion, compared to accomplishments to date.

Requirements	Target	Demonstrated
Leak rate	< 0.005 sccm/He	10^{-4} sccm/He at 800 psi
Response time	< 10 ms	< 10 ms
Inlet pressure	300~ 3000 psi	0~1000 psi
Power	< 1 W	~ 4 mW (static)
Temperature	0 ~ 75 °C	Not tested yet.

Solenoid-based miniaturized valves have been developed [1]. Some of these valves meet most of micropropulsion requirements. However, they still consume several Watts to operate the valves. Microspacecraft systems are anticipated to have severely limited power budgets. It is therefore desirable to incorporate "low power" valves meeting all the requirements for micropropulsion. Other previously reported microvalves do not meet the requirements for pressure range and/or leak rate needed for micropropulsion [3-9]. Recently, leak-tight microvalves operating at 10 atm have been reported [10], which still fall short of pressure range. Thermally actuated microvalves usually have slow response time (~ 100 ms to complete a cycle) [4-7], which is unacceptable for micropropulsion applications. This is because the slow valve actuation time causes long thruster on-times and wide impulse bits. Thermally actuated valves also suffer from the risk of random valve opening if ambient heating or cooling occurs, resulting in uncontrolled initiation of the actuation mechanism. Most microvalves reported previously have shown marginal valve seating at high pressures. Microvalves without adequate seating are exposed to severe problems in leakage and pressure handling capability. Therefore, significant efforts are required for the development of high-pressure microvalves to meet the micropropulsion requirements. In this paper, we present a fully characterized leak-tight piezoelectric microvalve, operating under extremely high inlet pressures for micropropulsion applications.

DESIGN OF MICROVALVE

The piezoelectric microvalve described in this paper consists of a seat plate, a boss plate and an actuator as shown in Figure 1. The microvalve components do not contain fragile membranes in order to allow high-pressure operation. Major elements of the microvalve design include its seating configuration with narrow seat rings. The seating configuration is provided by an initial opening pressure attributable to the tensile stress in the silicon tether extended by the valve seat as shown in Figure 2. A series of narrow rings on the seat plate is designed to reduce potential leakage due to scratches over a seat ring. The narrow rings reduce contact area, increasing the seating pressure and consequently reducing internal leaks. An additional advantage of the narrow/hard-seat design is that contact pressures may be high enough to crush contaminant particles, thereby also reducing the leakage attributable to contaminants in the flow. The boss plate has a 2 μm thick silicon dioxide layer as a hard seat material in the boss-center plate. The outer part of the boss plate is a metal-to-metal compression bonded to the seat plate. The boss-center plate covered by the silicon dioxide is slightly thicker than the outer part. This causes the boss-center plate to be pressed toward the seat plate by the stretched tether, enhancing a leak-tight valve operation. The piezoelectric stack actuator exhibits a very high block-pressure (50 MPa in this case), providing enough pressure to overcome the high differential pressure in addition to the downward bending stress from the tethers. The custom designed stack of piezoelectric actuators consists of active zones and an inactive central zone. The piezoelectric stack with mechanically separated (by deep U-grooves) active zones is bonded to the boss plate within a rigid housing. Application of a potential (~40 V) to the stack makes the active zones vertically expand by 5 μm, lifting the boss center plate, which is bonded to the inactive zone of the stack, away from the seat plate. This actuation creates a channel between the two openings, allowing for the passage of fluids as shown in Figure 3. Since the piezoelectric element is essentially a stacked capacitor, the actuator consumes an extremely low power when it is not moving, thus making it possible to achieve a nearly zero-power, normally-closed valve system.

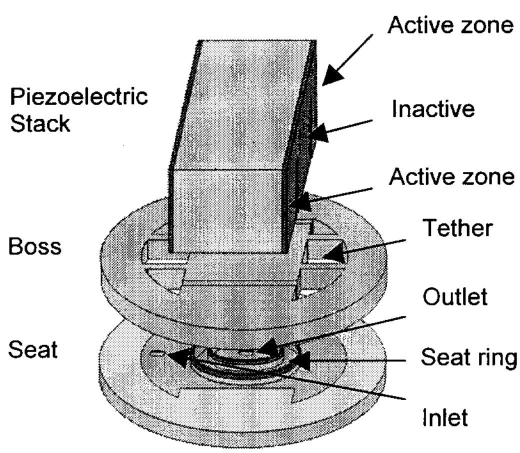

Figure 1 Concept schematic of the leak-tight piezoelectric microvalve.

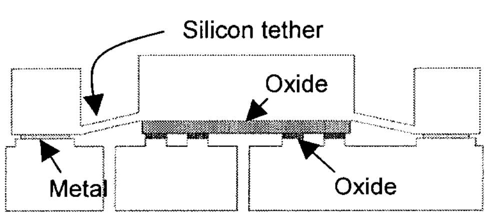

Figure 2 Configuration of the stretched silicon tethers by the extended valve seat.

IMPLEMENTATION

The silicon components are fabricated mainly by deep trench etching process before and after depositing and patterning metal layers. The seating rings are defined on the valve seat. The seat wafer is then etched from the backside to open up vias for the ports. These are metallized and patterned to define the bonding surfaces. The boss (or valve flap) wafer is then patterned from the topside to define the boss, which is released in a final etch. A silicon dioxide layer is deposited and patterned on the boss-center plate, followed by the deposition and patterning of bonding metals on the outer part of the boss and seat plates. The boss and seat wafers are then bonded to create a sealed and yet variable passage between the inlet and the outlet. This microfabricated structure, together with the piezoelectric actuator, is the primary valve component. The piezoelectric stack actuator is then bonded onto the boss plate in a leak-proof, high-pressure tolerant metal packaging. Figure 4 shows SEM micrographs of the fabricated silicon components of a microvalve. Figure 5 depicts a photograph

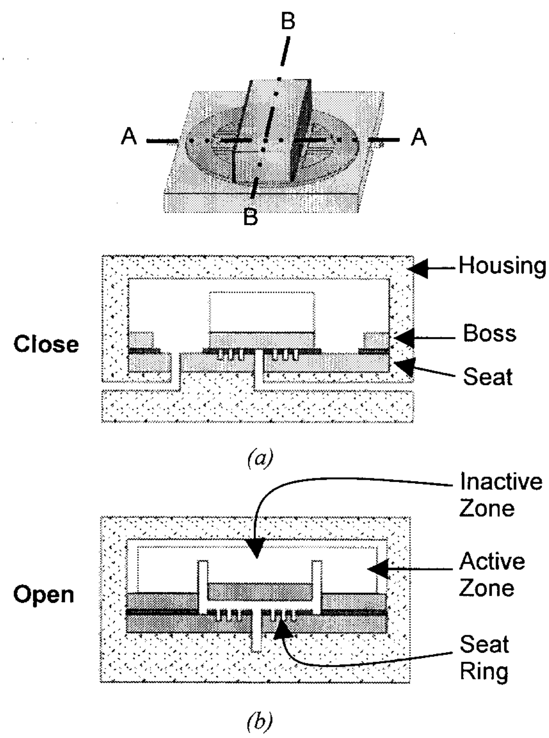

Figure 3 Operation principle of the normally-closed, leak-tight, high-pressure piezoelectric microvalve. Application of a potential (~40V) to the stack make the active zones vertically expand by 5 μm, lifting the boss center plate (bonded to the inactive zone of the stack) away from the seat plate. This actuation creates a channel between the two openings, allowing for the passage of fluids (a) Microvalve closed (cross-section A-A) (b) Microvalve opened (cross-section B-B)

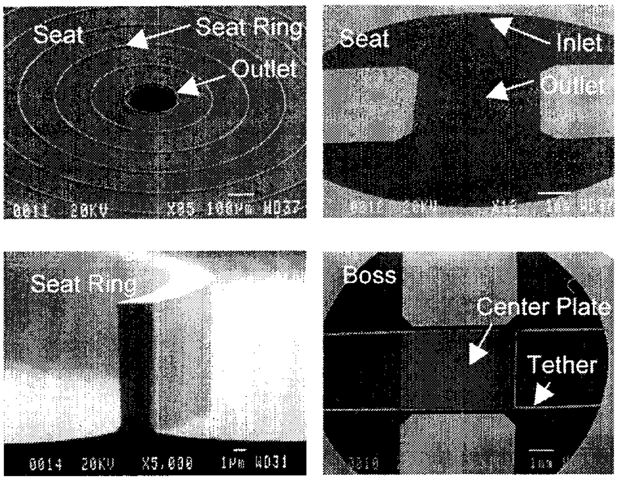

Figure 4 SEM micrographs of the seat plate and the boss plate. Top surfaces of seat rings are covered by 0.5 μm thick thermal oxide.

of a packaged microvalve. The package is a leak-proof stainless steel housing. Smaller (< 10 cm^2) and lighter (< 10 gm) titanium packaging for this microvalve design is currently under development.

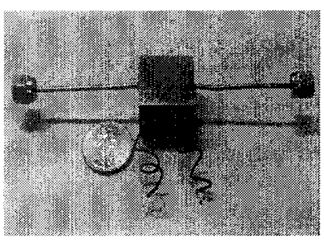

Figure 5 Packaged high-pressure piezoelectric microvalve.

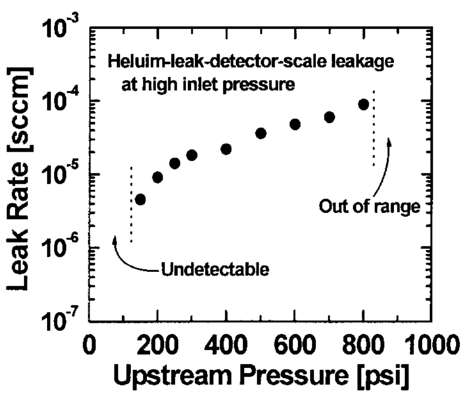

Figure 6 Measured internal leak rate of a normally-closed (non-actuated) valve is $9x10^{-5}$ sccm at the inlet pressure of 800 psi. The leakage is undetectable at pressures below 150 psi.

Fabricated microvalves have been tested at upstream pressures of up to 1000 psi. Testing beyond 1000 psi has not been performed due to the safety limit of current test setup. The leak test of a microvalve reveals an extremely low, 'helium leak detector scale' leak rate (10^{-4} sccm) at the pressure of 800 psi as shown in Figure 6. The leak is undetectable at the pressures below 150 psi. Figure 7 presents static forward flow rates of an actuated microvalve at variable applied potentials and pressures. The flow rate of a microvalve, with 10 V applied, is 52 sccm at the inlet pressure of 300 psi. Figure 8 shows the flow rates of a microvalve actuated with pulse width modulation. Figure 9 presents the flow rates at frequencies from 10 Hz to 10 kHz with a sinusoidal voltage of +/- 10 V.

Typical solenoid-based valves, if they are incorporated for micropropulsion systems, require the operation in pulse width modulation to provide necessary proportional flow control. On the other hand, piezoelectric microvalves do not need the pulse width modulation operation, because the actuation is proportional to the applied potential. Since the piezoelectric actuator consumes little power when it is not moving, it would ensure nearly zero-power microvalve operations during the firing action of microthrusters. The measured static (DC) power consumption, to hold the microvalve seat fully open, is 3 mW at 30 V as illustrated

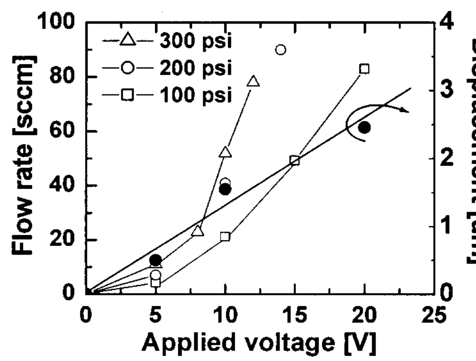

Figure 7 Measured flow rates of an actuated microvalve. The piezoelectric actuation has been successfully demonstrated at the pressures in the range of 0~1000 psi. Measured flow rates beyond 300 psi are out of range of the flow meter used in the tests.

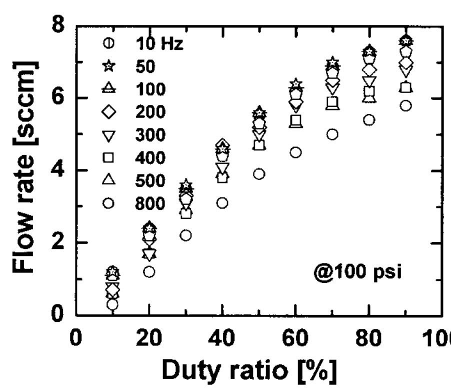

Figure 8 Measured flow rates of a microvalve actuated with pulse width modulation at 100 psi. (Applied 10 V square pulse)

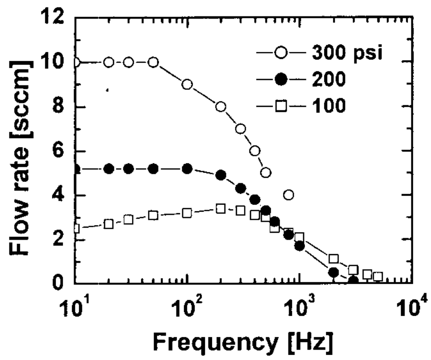

Figure 9 Measured flow rates of a microvalve at a wide frequency range, demonstrating a fast (< 10 ms) valve operation. (Applied +/- 10 V sine wave)

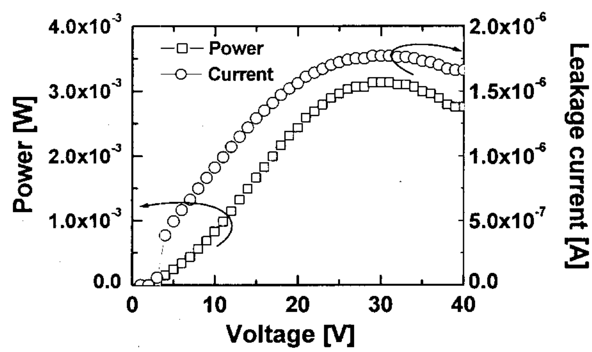

Figure 10 Measured power consumption of the piezoelectric actuator to hold the microvalve seat open.

in Figure 10. This power consumption is mainly due to the leak current in the piezoelectric stack. The dynamic (AC) power consumption of a microvalve, obtained from the measured phase difference between the voltage from a signal generator and the current to a valve actuator, is 180 mW at 100 Hz. These numbers will be further reduced to a few micro Watts-level for the second-generation piezoelectric microvalves currently under development. The test results of the microvalves described in this paper assure the successful demonstration of the leak-tight, fast, low power, and reliable microvalve technology, meeting the requisite micropropulsion requirements for NASA's microspacecraft architectures.

CONCLUSIONS

A leak-tight, high-pressure piezoelectric microvalve technology has been demonstrated for ultimate micropropulsion applications. The microvalve incorporates a custom designed piezoelectric stack actuator to provide high-pressure operation capability. A hard seating configuration using a series of narrow concentric seat rings contributes to the enhanced leak-tight microvalve operation. An extremely low leak rate of 10^{-4} sccm has been demonstrated at 800psi. The leakage is not detectable at the inlet pressures below 150 psi. The availability of such microvalves is expected to "open several doors" in microfluidics applications. In micropropulsion, it will allow thruster modules that can be used in very small spacecraft to provide attitude control functions. This microvalve technology will allow for a tight integration of fluidic devices with other MEMS components, such as the thrusters, or sensors and electronics.

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